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CARDIAC COMPUTED TOMOGRAPHY (S ACHENBACH AND T VILLINES, SECTION EDITOR)

Low Radiation Coronary CT

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Abstract With the increasing use of coronary computed tomography angiography (CCTA) as a noninvasive tool to evaluate for coronary artery disease, physicians who request, perform, or interpret these studies should be aware of the associated potential risks of ionizing radiation. This article provides an overview of radiation issues in CT, the risks of diagnostic-level ionizing radiation, and strategies that can be adopted to minimize exposure to radiation of patients undergoing CCTA.

Keywords Coronary CT · Coronary artery disease · Ionizing radiation risks

Introduction

Coronary computed tomography angiography (CCTA) has become increasingly adopted in clinical practice. However, the increasing use of CT in general along with high radiation doses reported in some initial CCTA studies has raised concerns among both the medical community and the general public of excessive exposure to radiation [1••–5]. Fortunately, a plethora of data has emerged demonstrating the potential for significant radiation dose reduction in CCTA via a number of techniques and practice strategies (Fig. 1).

Overview of Radiation in CT

Computed tomography dose index (CTDI) is the primary unit for radiation exposure measurement in CT, and represents an estimated average radiation exposure within the scan volume for a standardized phantom using the scanner output parameters [1••, 3]. As a result, CTDI does not account for individual patient-specific parameters such as size, shape, tissue composition, or even the body part being scanned [1••, 3, 12••]. Nevertheless, the total absorbed dose of radiation for a given scan protocol can be estimated by the dose–length product (DLP), which is calculated by multiplying the CTDI by the scan length [1••, 3, 12••]:

$$\mathrm{DLP}(\mathrm{mGy{\cdot}cm}) = \mathrm{CTDI}(\mathrm{mGy}) \times \mathrm{scan\,length}(\mathrm{cm})$$

Given that the potential biological effects from radiation depend on both the radiation dose absorbed and the biological sensitivity of the tissue or organ irradiated, the concept of effective dose, measured in milli-Sieverts (mSV), was introduced. As a result, the potential harmful effects from a CT examination can be compared with other radiation risks (e.g. annual level of background radiation in the US is 3 mSv) [1••, 3, 12••]. The effective dose can be estimated by multiplying the DLP by a conversion factor k which varies with the body region being imaged [3, 12••], with a k value of 0.014 mSv per mGy·cm currently being used for the adult chest [2, 12••].

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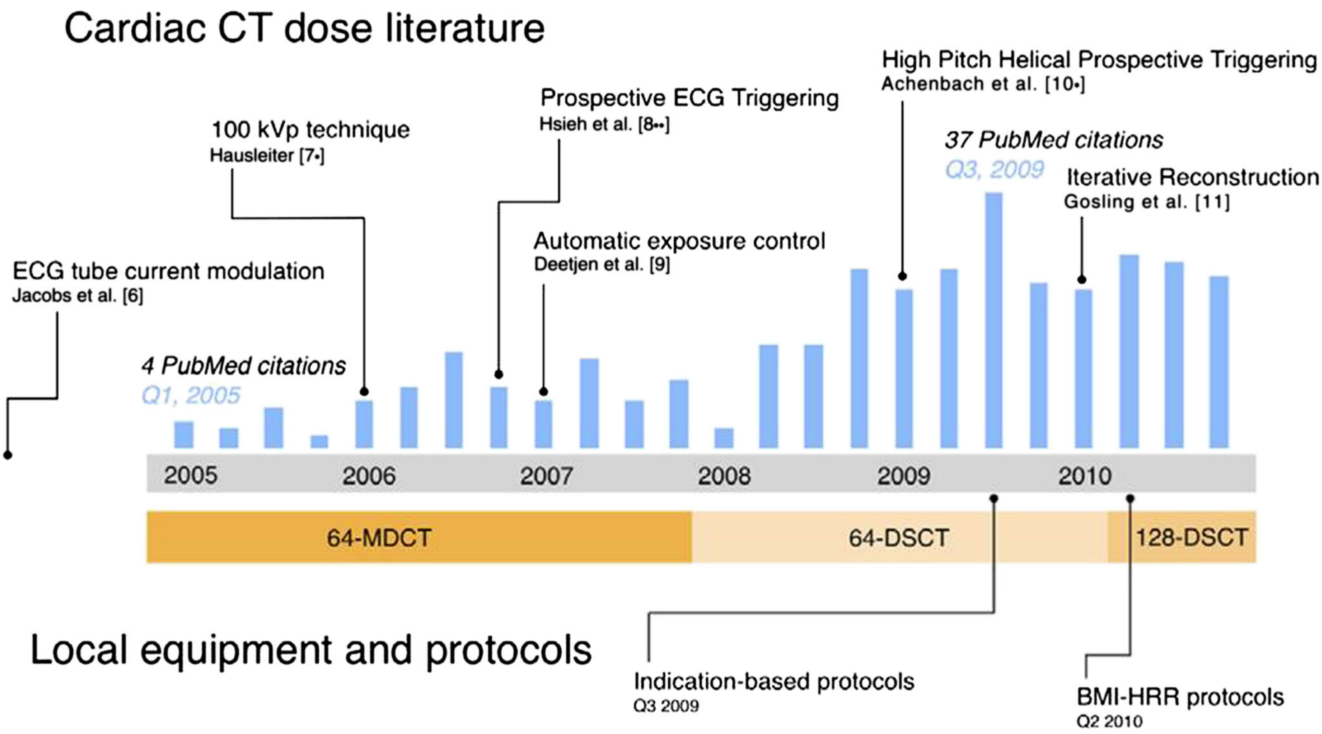


Fig. 1 Study period and context: The time-line shows total quarterly PubMed citations (*blue bars*) resulting from the search "cardiac CT dose reduction" and notes key developments in the cardiac CT literature during the study period. The locally available equipment during the study period is listed beneath (*CT* computed tomography, *DSCT* dual-source computed tomography, *MDCT* multidetector computed tomography). Reprinted with permission from: Ghoshhajra et al. [59•]

Biological Effects of Low-Level Ionizing Radiation in CT

Ionizing radiation, such as x-rays that are used in CT, is able to induce biological injuries via two mechanisms: (1) indirect injury through creation of hydroxyl radicals which interact with nearby DNA and cause damage, and (2) direct injury through ionization of DNA. Also important is the distinction between stochastic and deterministic effects of radiation. In general, the doses that are delivered by diagnostic-level CT are low and not high enough to cause deterministic effects (in contrast to, for example, therapeutic radiotherapy doses). Thus stochastic effects are the primary concern in diagnostic imaging [2, 13]. Stochastic effects are presumed to have no lower radiation dose threshold and are believed to be a result of cumulative exposures with a long period of latency [2, 13]. Clinically, stochastic effects manifest as either increased risk of cancer or genetic defects. Most of the quantitative estimates of radiation-induced cancer risk are derived from the survivors of the 1945 atomic bomb in Japan. Since the doses received in CT are significantly lower than those received by these survivors, estimation of cancer risk from CT requires extrapolation of the data [2, 13]. The International Commission on Radiologic Protection (ICRP) estimates 50 additional fatal cancers per 1,000,0000 people with 1 mSv of radiation exposure [12••, 13].

In addition to the amount of radiation exposure, several other factors play a role in determining the risk of radiation-induced carcinogenesis. One such factor is the gender of the patient, with women having a greater risk than men for the same level of exposure due to the presence of breast tissue [12••, 13]. Compared to larger patients with the same radiation exposure, smaller patients are also at increased risk due to higher amounts of radiation being absorbed in a greater number of radiosensitive organs [12••, 14]. Due to increased radiosensitivity, a longer life expectancy, and a longer latency period for stochastic effects, younger patients are at greater risk than older patients with the same radiation exposure. Indeed, radiation-induced cancer risks have been traditionally assumed to decrease with increasing age at exposure. However, a more recent analysis of the radiation-induced cancer risks in the Japanese survivors of the atomic bomb suggested that the risks after exposure in middle age may be up to twice as high as previously estimated due to radiation-induced promotion of preexisting premalignant cells [14, 15•].

Radiation Dose Reduction Strategies

Indication for the Examination

The most effective strategy for reducing the amount of radiation exposure is to avoid performing unnecessary radiological examinations. To this end, the American College of Radiology

(ACR) has published the ACR Appropriateness Criteria®, which is a set of evidence-based guidelines on appropriate use of radiological examinations. The criteria for cardiac imaging can be found on the ACR website: https://acsearch.acr.org/list. In addition, the Cardiac Computed Tomography Writing Group has published an updated 2010 Appropriate Use Criteria for Cardiac Computed Tomography document, which can be found at http://circ.ahajournals.org/content/122/21/e525. While these guidelines serve as useful references, appropriate indications for CCTA can vary among institutions based on the availability of resources such as scanners or local expertise, and there is no substitute for close communication between the imager and the referring clinician.

Scan Modes

One of the most important user-adjustable parameters that define the amount of radiation exposure is the mode of electrocardiogram (ECG) synchronization. ECG-gated scans can be acquired in either axial or helical modes. In order to obtain data at a specific phase of the cardiac cycle, ECG synchronization is assigned in either a prospective or retrospective manner. For prospective ECG-triggered modes, axial acquisition is performed during only the desired phase of the cardiac cycle (Fig. 2). An exception to this is scanners that can achieve a very high pitch (helical-mode table feed per rotation) value, with which a high-pitch helical scan can be performed with prospective ECG triggering [15•, 16]. The benefit of prospective ECG triggering is a significant radiation exposure reduction, at the expense of only limited phase acquisitions. In selected patients with favorable heart rates, this has been shown to be highly effective [16–18] although with modern hybrid "padded" modes and advanced arrhythmia rejection, the appropriate use of prospective triggering has been extended to a wider range of patients [12••, 17, 18].

Conversely, in retrospective ECG-gated modes, a low-pitch helical scan is performed continuously throughout the cardiac cycle [12••, 19]. Data are then retrospectively selected at favorable time points during the cardiac cycle for image reconstruction. Due to the low pitch, there is significant (up to 80 %) overlap of successive acquisitions during a retrospectively ECG-gated scan. In order to reduce the exposure, most retrospectively ECG-gated acquisitions are performed with ECG-based tube current modulation, whereby the scanner tube output is downregulated during phases of the cardiac cycle less likely to be necessary for image reconstruction. For example, in a patient with a slow, regular rate and rhythm, tube current can be modulated downward during systole, since the dataset will likely be motion-free in late diastole (Fig. 2) [19, 20••].

Retrospective ECG-gated acquisition was considered the conventional technique for CCTA. Hsieh et al. were the first to describe prospective ECG-triggered acquisition in 2006 (Fig. 2) [20••, 21], and this has subsequently become more popular due to lower radiation exposure. Husmann et al. in 2007 reported early experience with prospective ECG triggering, with which they observed a mean radiation dose of 2.1 mSv, compared to higher doses reported in the literature at the time for retrospective ECG gating (21.4 mSv without ECG pulsing; 9.4 mSv with ECG pulsing) [21, 22]. Shuman et al. performed whole-chest CT in consecutive patients presenting with chest pain to the emergency department. They found a mean effective radiation dose of 31.8±5.1 mSv with retrospective ECG gating, compared to a mean effective radiation dose of 9.2±2.2 mSv with prospective ECG triggering at 71 % of the cardiac cycle [12••, 22]. Therefore, prospective

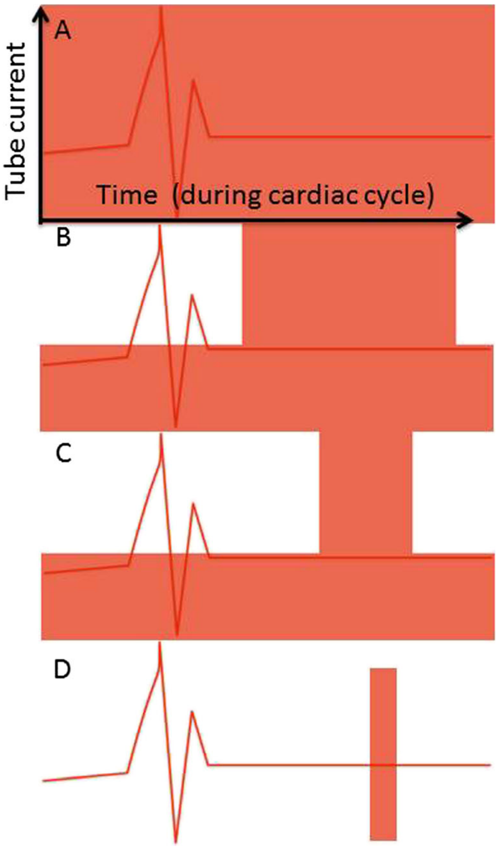


Fig. 2 Scan mode and ECG modulation. Retrospective ECG-gated acquisition was initially the conventional technique for CCTA, where the full tube current (*shaded red*) is maintained throughout the entire cardiac cycle (**a**). With ECG tube current modulation (i.e. ECG pulsing), the tube current is reduced during systole in order to lower the amount of radiation dose (**b**). Further radiation reduction could be achieved by limiting the duration of full tube current to either the end-systole or the late-diastole (**c**) windows. Prospectively ECG-triggered acquisition (**d**) results in a lower radiation dose than retrospective ECG-gated acquisition (**a**–**c**) by turning the tube current completely off for data acquisition outside the desirable phases. Note that for retrospectively ECG-gated modes (**a**–**c**), helical-mode acquisitions are performed with up to 80 % *z*-axis overlap between rotations, whereas in prospectively ECG-triggered modes, the *z*-axis overlap between acquisitions is approximately 10 % (or, in "single-heartbeat" modes, non-existent), which further reduces radiation exposure

ECG triggering should be strongly considered in patients with a low heart rate, and is recommended by societal guidelines [12••, 23, 24].

With the advent of second-generation dual-source CT (DSCT) scanners and 320 detector row scanners, "single heartbeat" imaging became possible in some situations. Second-generation DSCT utilizes a high-pitch (i.e. pitch >3) helical mode with a temporal resolution of 75 ms, combined with prospective ECG triggering to minimize radiation dose [23–25], and may be an option in patients in whom the ability to reconstruct images at specific phases of the cardiac cycle is not required, or if needed, a second scan would be permissible. Our early experience has revealed that in approximately 20 % of patients the use of this mode results in non-evaluable coronary segments, with the most common reasons being extensive motion, noise, and streak artifacts due to extensive calcifications [25, 26]. On the other hand, in patients with a low and stable heart rate with lower pretest probability of coronary artery disease and/or low coronary calcium burden, the use of this high-pitch helical mode has been shown to markedly reduce radiation dose with acceptable image quality [26–28]. The 320-multidetector row scanner allows acquisition of the entire *z*-axis of the heart in a single gantry rotation, thus eliminating the possibility of misalignment artifact and extraneous radiation exposure due to overlapping acquisitions [27, 28]. However, due to the temporal resolution of a single-source technique, a relatively low heart rate (up to approximately 75 bpm) is required for this single-heart-beat acquisition [28, 29], at which point multiple heartbeats and multisegment reconstruction techniques are required.

Patient Preparation: Breast Displacement

Given the high radiosensitivity of breast tissue and an increased incidence of breast cancer in women exposed to large doses of radiation, breast exposure in female patients undergoing CCTA examination should be minimized [29]. In a study performed by Foley et al. [12••, 29, 30], breast displacement alone resulted in a mean 24 % reduction in breast surface radiation dose without affecting image quality of the examination. This strategy is particularly beneficial in patients with larger breasts (Fig. 3). Furthermore, Foley et al. found that the use of breast shielding resulted in an additional mean 16 % reduction compared to breast displacement alone. However, it should be noted that if anatomic-based tube current modulation is to be used (discussed below), the breast shields should be placed after completion of the topograms. Otherwise, the scanner may actually increase the dose while scanning over the body region with breast shielding [12••, 30, 31]. Hulten et al. found that the use of breast shields resulted in slightly increased noise. Therefore its use in women undergoing coronary angiography requires further study [12••, 31]. The Society of Cardiac Computed Tomography (SCCT) guidelines on radiation dose and dose-optimization strategies in cardiovascular CT recommend against the use of breast shields [12••].

Patient Factors

Heart Rate and Rhythm Considerations

In general, a low heart rate is preferred since image acquisition in CCTA has been conventionally performed during diastole, and a low heart rate is required for scan modes such as prospective ECG-triggered axial scanning and prospective ECG-triggered high-pitch helical scanning (see above) [12••]. Guidelines recommend the use of prospective ECG-triggered axial scanning in patients with a heart rate less than 60 to 65 bpm, with retrospective ECG-gated helical scanning used in patients with a higher heart rate [12••, 32].

Heart rhythm is known to play a role in determining the amount of radiation exposure, and in a study performed by Techasith et al. [32], patients with arrhythmias including premature atrial contraction or premature ventricular contraction were found to have higher radiation exposure than patients with a normal sinus rhythm, and patients with atrial fibrillation received the highest amount of radiation. This was mainly due to widening of the tube current modulation window width when the R–R interval was irregular, resulting in an increased interval in which the tube current was not modulated (i.e. at 100 % capacity) [32, 33].

Over the past several years, however, systolic scanning has emerged as a feasible option. Bamberg et al. studied the use of systolic scanning in patients undergoing retrospective ECG-gated helical scanning, and found a significant reduction in radiation exposure with systolic than with diastolic scanning (4.97±2.3 mSv versus 9.38±5.5 mSv) while preserving imaging quality [33, 34]. In a study of patients scanned with prospective ECG-triggered axial mode, Feuchtner et al. compared the use of systolic scanning (at 40 % R–R interval) in patients with a heart rate >65 bpm and diastolic scanning (at 70 % R–R interval) in patients with a heart rate <65 bpm [34]. They found no difference in image quality of the coronary arteries between the two groups of patients, with systolic scanning offering the additional ability to quantify left ventricular function and regional wall motion abnormalities [17, 34]. These studies therefore highlight the potential for use of systolic scanning to scan patients with a higher heart rate, obviating or reducing the need to administer beta blockers yet still reducing radiation exposure.

Furthermore, patients with arrhythmias have traditionally been scanned with retrospective ECG-gated helical scans to achieve diagnostic quality images, which unfortunately further increases the amount of radiation exposure. Our investigators [17, 18] have investigated the use of prospective ECG-triggered axial scan mode with a arrhythmia rejection algorithm, which resulted in a decrease in radiation exposure by

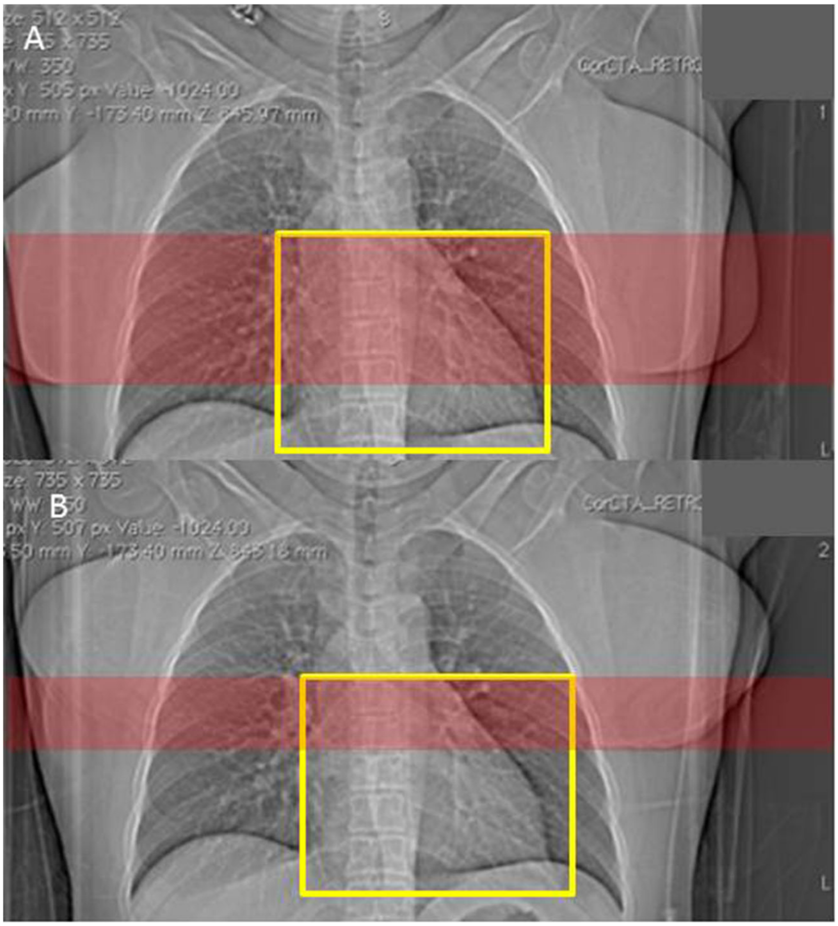


Fig. 3 Breast displacement **a** CT topogram before breast displacement shows that a considerable amount of breast tissue (*shaded red*) lies within the scan acquisition range (*yellow box*). **b** On the other hand, the CT topogram in the same patient acquired after breast displacement with the scanner table's safety holder shows that most breast tissue has been displaced cranially and outside the planned scan acquisition range (*yellow box*), with only a minimal amount of inferior breast tissue in the scan range (*shaded red*)

approximately 50 % compared to retrospective ECG-gated helical mode, with preservation of image quality. The disadvantage of this approach is a potentially increased scan time, which requires the administration of an additional amount of contrast agent to maintain adequate opacification of the coronary tree. These modes have been confirmed to be efficacious at a wide range of heart rates [12••, 17, 18, 35].

Body Size Considerations

In smaller patients with a decreased amount of subcutaneous tissue, the scan parameters affecting the amount of radiation (i.e. tube potential and tube current) can safely be reduced while still maintaining the signal-to-noise ratio required for evaluation of the coronary arteries [12••, 35]. The use of body mass index (BMI) has been the most commonly used parameter for modulating radiation. For instance, Alkadhi et al. found a dose reduction of approximately 50 % following reductions in both tube potential from 120 kV to 100 kV and tube current from 330 mAs to 190 mAs in patients with a BMI of less than 25 kg/m^2 [35, 36]. However, our investigators have observed that the association between BMI and chest area is weak in certain patients, possibly due to differences in composition of body tissues inside and outside the scan range, potentially resulting in either over-exposure or under-exposure [36]. Instead, anthropometric measures such as chest area or the patient's body image obtained through the topogram can be used to modulate the amount of radiation required [36, 37].

Our investigators subsequently demonstrated that the combined use of automated tube current and potential modulation resulted in a reduction in radiation exposure of approximately 30 %, along with increased signal-to-noise and contrast-to-noise ratios in certain coronary artery segments (Fig. 4) [37, 38]. Winklehner et al. studied the use of automatic attenuation-based tube potential selection in patients with a BMI in the range 18.8 – 33.8 kg/m^2 undergoing non-ECG-gated thoracoabdominal CT angiography, which resulted in an overall dose reduction of approximately 25 % when compared with a standard 120 kV protocol while preserving diagnostic image quality [38, 39]. Layritz et al. also found that the use of automated attenuation-based selection of tube current and voltage resulted in a reduction in radiation while maintaining image quality and was superior to expert BMI-based selection [12••, 16, 39, 40].

Therefore, in scanners which support the use of automated tube potential or current selection based on the tomogram, such options should be strongly considered (discussed below).

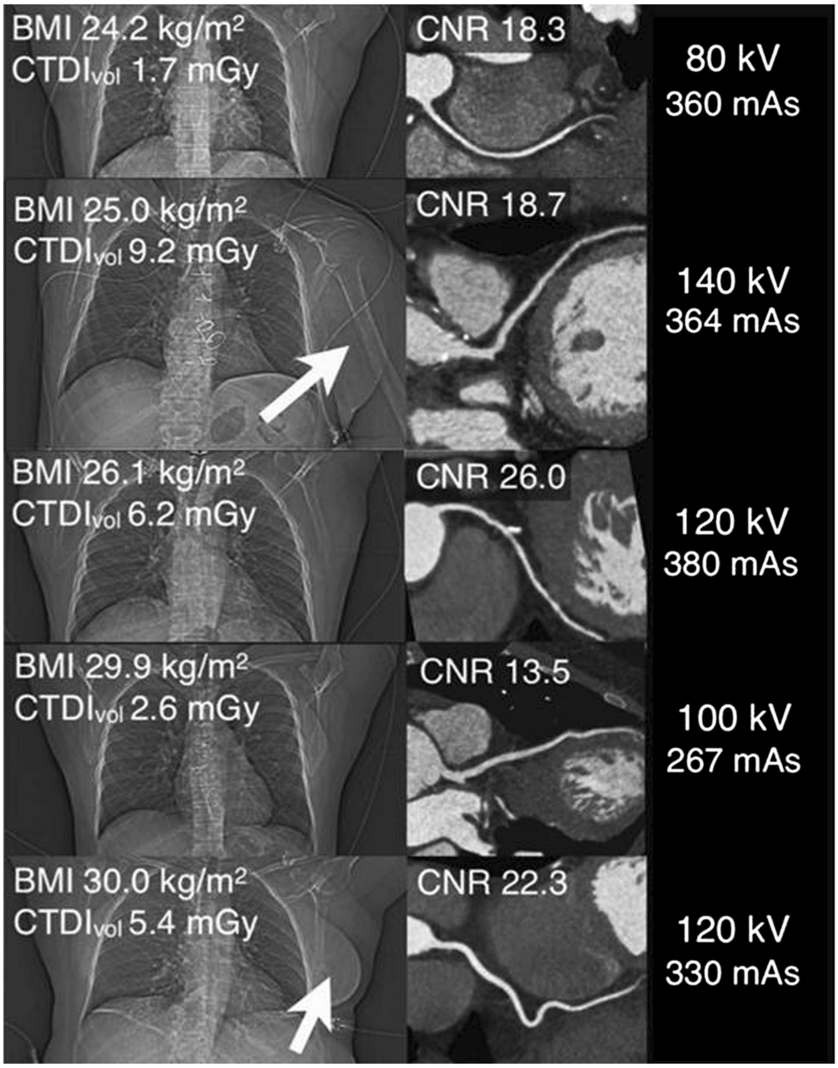


Fig. 4 Scout radiographs and curved multiplanar reconstruction images in five patients scanned using automatic potential selection with automatic exposure control. All radiographs were deemed diagnostic for all coronary segments. All scans were acquired in the prospective ECG-triggered high-pitch helical acquisition mode, resulting in all parameters affecting dose being held constant, except tube potential and tube current. BMI and radiation exposure (CTDIvol) did not show an obvious correlation, nor did tube potential and contrast-to-noise ratio (CNR). In some images attenuating structures are present in the scan field of view (*arrows*) where higher tube potentials were selected. One patient had experienced a cerebrovascular accident and was unable to raise his arm; another patient had large breasts that could not be displaced from the scan field of view. Note that either site-specific or SCCT empiric BMI-based guidelines were used. Reprinted with permission from: Ghoshhajra et al. [37]

Scan Parameters

Scan Length

It is imperative that the scan length be set to the minimum necessary to answer the clinical question in order to minimize radiation exposure [12••, 16, 40, 41]. The use of a noncontrast (or "calcium scoring") examination to tailor the scan length has been shown to benefit the scan range by reducing the scan length [12••, 41]. However, calcium scoring may not be beneficial in younger patients in whom it is unlikely to add prognostic information or to lead to a change in scan parameters.

Tube Potential

In CT, radiation exposure is proportional to the square of the tube potential (measured in kilovolts), while image noise is proportional to the inverse of tube potential [12••]. For instance, a reduction in tube potential from 120 kV to 100 kV results in a 31 % reduction in radiation dose, with a corresponding 20 % increase in image noise [12••, 42–47]. As a result, although CCTA has traditionally been performed with 120 kV, multiple studies have been performed to investigate the possibility of decreasing tube potential to 100 kV or even 80 kV to minimize radiation exposure [42–47].

In the PROTECTION I (Prospective Multicenter Study on Radiation Dose Estimates Of Cardiac CT Angiography I) study, the use of a 100-kV protocol instead of a 120-kV protocol in non-obese patients resulted in a 53 % reduction in radiation dose estimates [42]. More importantly, although the amount of image noise increased, both the signal-to-noise and contrast-to-noise ratios also increased, with overall no impairment in diagnostic image quality [42, 46]. Engel et al. found that an 80-kV protocol instead of a 100-kV protocol (mean doses 83.0 mGy·cm and 193.0 mGy·cm, respectively) in non-obese patients resulted in a significantly lower radiation dose with preservation of subjective image quality [46, 47]. Leipsic et al. performed a prospective randomized trial in

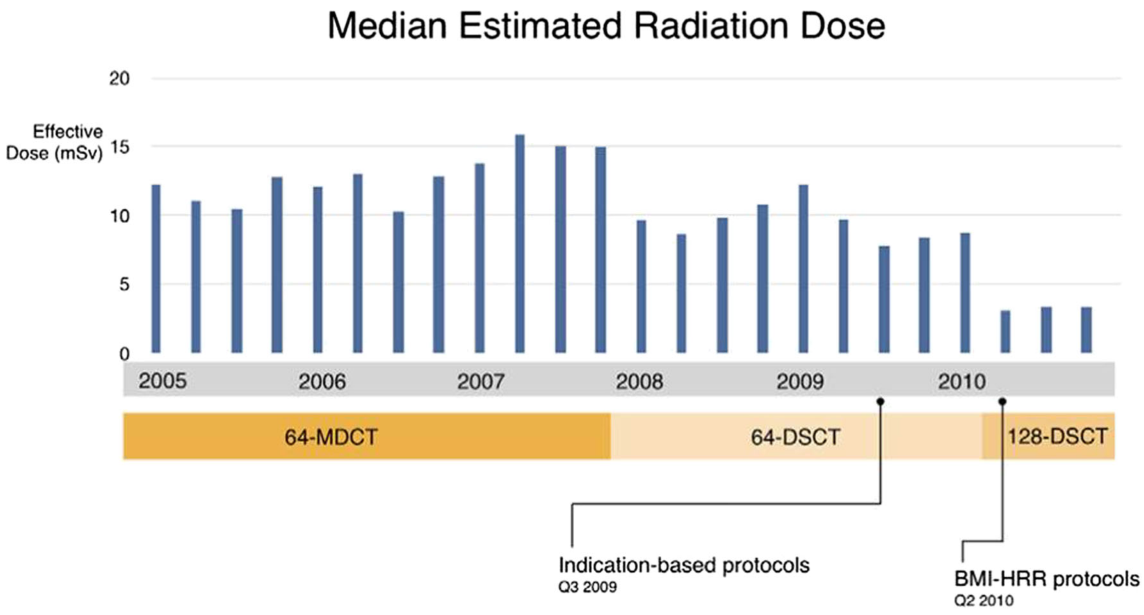


Fig. 5 Unadjusted median estimated radiation dose versus scanner and protocol type. Progressive decreases in radiation doses were documented with successive scanners and protocols (*BMI* body mass index, *HRR* heart rate and rhythm, *DSCT* dual-source computed tomography, *MDCT* multidetector computed tomography, *Q2* quarter 2, *Q3* quarter 3). Reprinted with permission from: Ghoshhajra et al. [59•]

50 consecutive patients referred for invasive catheter angiography (ICA) with a BMI ≤35 kg/m^2 [47, 48]. Patients were randomly assigned to either a standard tube voltage protocol (100 kV if BMI <25 kg/m^2; 120 kV if BMI 25 to 35 kg/m^2) or a reduced voltage protocol (80 kV if BMI <25 kg/m^2; 100 kV if BMI 25 to 35 kg/m^2) with a fixed tube current. No differences in signal-to-noise ratio, contrast-to-noise ratio or image quality between the two protocols on a per-patient, per-artery, or per-segment basis were found. Furthermore, when compared to quantitative coronary angiography, there were no differences in sensitivity, specificity, or accuracy between the two groups.

On the other hand, although an increased amount of radiation is generally required for adequate penetration in larger patients, increasing the tube potential from 120 kV to 140 kV may not be justified. Our investigators retrospectively evaluated image quality and radiation exposure in overweight or moderately obese patients (BMI 25 to 35 kg/m^2) scanned with either a 120-kV protocol or a 140-kV protocol [12••, 48]. The image quality was similar between the two protocols, but the 140-kV protocol was associated with an approximately 35 % increase in effective radiation dose.

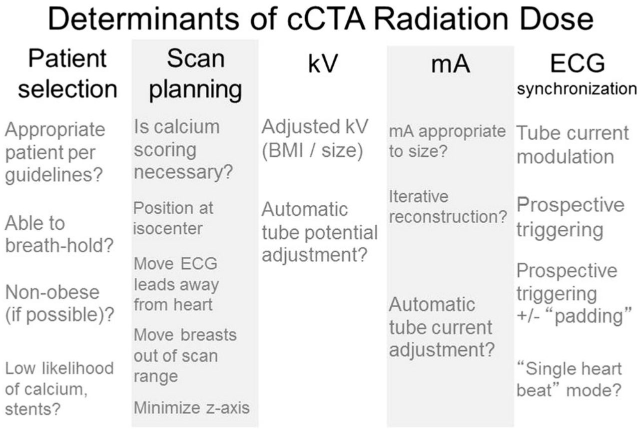
In conclusion, tube potential is a key determinant factor in the amount of radiation exposure. The SCCT guidelines recommend the selection of tube potential based on either BMI or weight, with 100 kV considered in patients weighing ≤90 kg or a BMI of ≤30 kg/m^2 [12••, 36, 37]. However, as previously discussed, automated tube potential selection based on the patient's topogram, if available on the scanner, is probably the preferred method for modulating tube potential selection [30, 36, 37].

Tube Current

Although tube current (expressed in milliamperes) affects radiation exposure in a linear manner (i.e. a 20 % reduction in tube current results in a 20 % reduction in radiation dose), most CT scanners are able to adjust tube current during the scan (unlike tube potential which is preselected and cannot be adjusted during the scan). Therefore, tube current modulation plays an important role in minimizing the radiation dose. In non-ECG-gated CT scanning, tube current can be modulated along the *z*-axis position of the scan, and in some cases as the beam rotates around the patient (*x*-*y* axis). In cardiac-gated scanning, tube current can also be modulated in the time domain, with modulation synchronized so as to be highest during the predicted most favorable time points during the cardiac cycle [30, 49], but tube current cannot be modulated along the *z*-axis of the scan range.

Mulkens et al. investigated the use of an automatic exposure control mechanism for dose optimization in CT examinations of multiple body regions [35, 49, 50]. In their study, both angular tube current modulation within the *x*-*y* plane and *z*-axis tube current modulation were used, allowing a mean dose reduction of 20 % for a thoracic examination while maintaining good image quality. Others have reported the use of BMI as a parameter for modulating tube current, allowing a reduction in radiation exposure while preserving image quality [12••, 35, 50]. The SCCT guidelines recognize the adjustment of tube current on the basis of patient size as a useful strategy to reduce radiation exposure [12••].

Given that diagnostic quality images of the coronary arteries can only be acquired during specific phases of the cardiac



Determinants of cCTA Radiation Dose

Patient selection
- Appropriate patient per guidelines?
- Able to breath-hold?
- Non-obese (if possible)?
- Low likelihood of calcium, stents?

Scan planning
- Is calcium scoring necessary?
- Position at isocenter
- Move ECG leads away from heart
- Move breasts out of scan range
- Minimize z-axis

kV
- Adjusted kV (BMI / size)
- Automatic tube potential adjustment?

mA
- mA appropriate to size?
- Iterative reconstruction?
- Automatic tube current adjustment?

ECG synchronization
- Tube current modulation
- Prospective triggering
- Prospective triggering +/- "padding"
- "Single heart beat" mode?

Fig. 6 The most common factors that affect both the resulting radiation dose and image quality of a CCTA examination. These factors should be considered when designing scan protocols and carefully reviewed prior to performing an examination

cycle (i.e. end-systole or late-diastole), the tube current for data acquisition outside these desirable phases can be reduced or turned off (i.e. in prospective triggering) to minimize radiation exposure (Fig. 2) [12••, 38•]. In patients with a stable sinus rhythm, Hausleiter demonstrated a reduction in radiation dose of approximately 35 % while maintaining diagnostic image quality when the tube current was reduced by 80 % in the remainder of the cardiac cycle during retrospective-gated helical diastolic acquisition [38•, 51]. Weustink et al. studied the use of ECG tube modulation in both systolic (31 – 47 % of R–R interval) and diastolic (60 – 76 % of R–R interval) acquisitions, with tube current reduction to 4 % when outside these windows. This approach resulted in a 43 % overall reduction in mean radiation dose when compared to a protocol without modulation [51, 52]. It should be noted that different vendors use different methods to specify the appropriate phase of the cardiac cycle, so the definition of appropriate time points for peak tube current during a cardiac cycle depends on the scanner make and model. For example, vendor A might specify a diastolic phase reconstruction as starting at 70 % of the R–R interval, while vendor B might specify that same 70 % R-R interval with the reconstruction centered at 70 % of the R-R interval. Thus, for a given heart rate, the same requested reconstruction (and thus ideal phase modulation) will be slightly different. This is further complicated by wide variations in the temporal resolution of single-source and dual-source scanners; careful manipulation of the targets for phase modulation in accordance with a site's technology is advised [12••, 52].

The use of ECG-based tube current modulation is recommended by the SCCT guidelines for retrospectively gated helical examinations [12••, 38•].

Combined Tube Potential and Current Modulation

Many vendors now allow tube current modulation to minimize radiation dose, and these options should strongly be considered. The use of tube potential (voltage) has even stronger effects, and should also be strongly

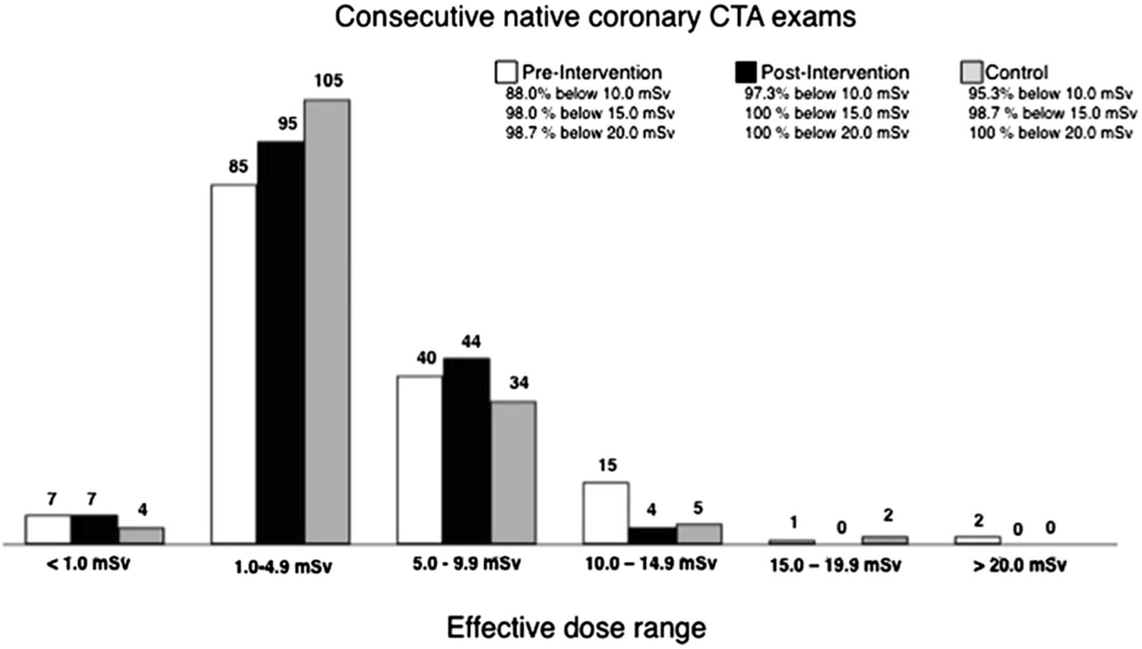


Fig. 7 Median estimated radiation doses in the in preintervention control period (*white*), the intervention period (*black*) and the late control group (*gray*) (*CTA* computed tomography angiography). Reprinted with permission from: Engel et al. [63]

considered. This was first reported on the basis of BMI by Hausleiter [38•, 46, 47], who used 100 kV in selected non-obese patients. Later, others reported the use of 80 kV in selected patients (i.e. BMI <25 kg/m^2) [37, 46, 47]. More recently, automatic selection of tube potential and concurrent modulation of tube current has been described. As discussed above, our group have demonstrated the use of automated tube current and potential modulation combined results in a reduction in radiation exposure of approximately 30 % while preserving diagnostic image quality [37, 53]. Similar results were found by Park et al. [39, 53] and Layritz et al. [39, 54], all groups reporting that the use of automated attenuation-based selection of tube current and voltage is superior to BMI-based selection, and achieves a reduction in radiation while maintaining image quality.

Image Reconstruction: Iterative Reconstruction

Instead of the default filtered back projection (FBP) reconstruction method conventionally used in CT, newer iterative reconstruction techniques have emerged that allow accurate reconstruction of images with noise reduction [54]. Silva et al. reported the ability of a vendor-specific iterative reconstruction technique, adaptive statistical iterative reconstruction, to reconstruct images of diagnostic quality at reduced radiation doses of up to 65 % [54, 55]. Bittencourt et al. investigated the use of iterative reconstruction specifically for cardiac CT, and found that the vendor-specific iterative reconstruction in image space technique resulted in a lower image noise of the coronary arteries compared to FBP [55, 56]. Yin et al. performed a prospective study in 60 patients who underwent ICA as well as two CCTA examinations, one using routine radiation dose settings with FBP and the other using a 50 % reduced tube current–time product with iterative reconstruction [56, 57]. Using ICA as the reference standard, image quality and diagnostic accuracy were preserved with iterative reconstruction, which achieved a 50 % reduction in radiation dose compared with routine FBP. Other vendor-specific iterative reconstruction algorithms such as the adaptive iterative reduction algorithm [57, 58] and the iDose4 algorithm [58, 59•] have also been reported to result in radiation reduction in CCTA.

A Comprehensive Approach to Clinical Cardiac CT Dose Reduction

All the factors and parameters discussed above should be considered for each patient undergoing CCTA to minimize radiation exposure while preserving diagnostic image quality. With the advances in CT scanner technology and in understanding cardiac CT physics, the radiation dose from a CCTA examination has been declining over the years. Our group studied the temporal changes in radiation dose from CCTA in a tertiary referral center involving 1,277 examinations from 2005 to 2010, using increasingly comprehensive yet progressively simplified protocols [59•–61]. We observed a median dose reduction of approximately 75 % from the beginning to the end of the study period as a result of the implementation of scanning protocols involving a number of the previously discussed factors (Fig. 5). The most significant factors were the use of lowered tube potential, and prospective triggering [62], when applicable. Our experience and data suggest that although CCTA requires physician supervision and acquisition cannot be fully automated, carefully designed protocols allow decreased radiation dose while maintaining high diagnostic image quality (Fig. 6).

Continuous Quality Assurance and Improvement

Systematic monitoring of radiation exposures is a key component of any hospital's dose reduction efforts [60, 61, 63] and, along with ongoing feedback to physicians and technologists, plays a vital role in overall dose reduction. This method of monitoring need not be expensive; at our site we use weekly dose reports in the form of an email in a tertiary referral center. This simple intervention has significantly reduced doses (3.4 mSv versus 4.1 mSv), and more importantly has reduced the proportion of high-exposure outliers (Fig. 7) [12••, 63]. The SCCT guidelines recommend systematic monitoring of radiation dose in a format that is readily available for retrieval and periodic review [12••].

Summary

This article reviews a variety of strategies that are readily available for radiation dose reduction in CCTA. When used appropriately, these strategies can be combined to yield a diagnostic examination with much reduced radiation exposure, therefore adhering to the ALARA (as low as reasonable achievable) principle.

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Compliance with Ethics Guidelines

Conflict of Interest Andy KW Chan, Maros Ferencik, and Suhny Abbara declare that they have no conflict of interest.

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Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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- • Of importance
- •• Of major importance

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